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THERMOMECHANICAL PROCESSING OF ALUMINUM ALLOY INGOTS

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The Materials Engineering Division at Frankford Arsenal is involved in an extensive research effort aimed at upgrading the engineering properties of wrought high strength 7000 series aluminum alloys through thermomechanical processing of the ingot material. The development of two new ingot thermomechanical processing techniques, ISML-ITMT and FA-ITMT, is presented. The effects of these techniques on the recrystallization behavior, grain morphology, tensile properties, fracture toughness and stress corrosion resistance of high purity 7075 alloy sheet and plate is presented. The recrystallization of

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20. ABSTRACT (Cont'd)

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Thermomechanical Processing of Aluminum Alloy Ingots

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ABSTRACT

The Materials Engineering Division at Frankford Arsenal is involved in an extensive research effort aimed at upgrading the engineering properties of wrought high strength 7000 series aluminum alloys through thermomechanical processing of the ingot material. The development of two new ingot thermomechanical processing techniques, ISML-ITMT and FA-ITMT, is presented. The effects of these techniques on the recrystallization behavior, grain morphology, tensile properties, fracture toughness and stress corrosion resistance of high purity 7075 alloy sheet and plate is presented. The recrystallization of 7075 alloy into a fine grained material was found to be controlled by the distribution of the major alloying elements, Zn, Mg and Cu, as well as by that of the ancillary element, Cr. The results showed that for a given standard temper, i. e., T6, T76 and T73, high purity ITMT processed 7075 alloy has finer grain size, equivalent strength and better ductility, fracture toughness and stress corrosion characteristics than commercial 7075 alloy. The work also showed that high purity ITMT processed 7075 alloy in the FTMT temper (a temper involving a deformation stage between an initial and a final artificial aging stage) has higher strength, ductility and fracture toughness than commercial 7075-T6 alloy.

INTRODUCTION

The major shortcomings of commercial high strength wrought 7000 series aluminum alloys are low ductility, low toughness and poor stress corrosion resistance, especially in the short transverse direction. Frankford Arsenal has been conducting studies aimed at eliminating these deficiencies and improving the strength of these alloys through the use of improved processing techniques. The early work in this area[1-4] showed that elimination of second phase constituents induced substantial improvements in ductility and toughness and some improvement in fatigue resistance at equivalent strength levels when compared to commercial alloys. These improvements were achieved by the use of high purity materials, by controlled solidification techniques to achieve a small dendrite arm spacing and by optimum homogenization treatments.

Other work directed towards improving the properties of 7000 series alloys, carried out at Istituto Sperimentale dei Metalli Leggeri (ISML) under a US/Italy cooperative research program, has been reported by DiRusso et al.[5,6] In that work, a new technique termed final thermal mechanical treatment (FTMT) was developed. This technique involves the application of plastic deformation between an initial and a final artificial aging step. With FTMT the strength of the 7000 series alloys can be increased by 20 to 25 pct with only a minimal loss of ductility and toughness.

In addition to the property improvements achieved by better solidification techniques and by advanced thermal mechanical treatments (FTMT), it was considered that improvements could also be achieved by controlling the grain morphology. Although there is much information on the effect of grain morphology

in pure metals and solid solution alloys little data are available regarding high strength aluminum alloys. Therefore, the US/Italy cooperative research program carried out at ISML also included investigations on grain morphology effects. The results of those studies[7-9] showed that in 7075 alloy the properties related to ductility, such as elongation, reduction in area, and toughness were improved by the use of an intermediate thermal mechanical treatment (ITMT) which was designed to produce a wrought product with grains that are finer than those obtained by conventional processing.

Realizing the broad potential that ITMT has on improving the performance of Army materiel, especially in such mill products as rolled plate, a broad program was initiated at Frankford Arsenal to study in more detail the various parameters involved in ingot processing. This paper presents the results concerned with the effect of selected experimental ingot processing treatments on the recrystallization behavior, grain morphology, tensile properties, fracture toughness, and stress corrosion resistance of wrought high purity homogeneous 7075 sheet and plate.

DESCRIPTION OF THERMOMECHANICAL PROCESSES

ITMT involves a new concept in ingot processing in that the original cast grain boundaries are eliminated by a recrystallization step prior to conventionally working the material into the final wrought products. In the ITMT process reported by DiRusso et al,[7-9] i.e., ISML-ITMT, the 7075 ingots are partially homogenized, worked at relatively low temperatures, recrystallized, homogenized and then conventionally hot worked into wrought products. The ITMT products can be utilized in the as-recrystallized (AR) condition or in the as-recrystallized plus hot rolled (AR+HR) condition.

According to DiRusso et al,[7-9] the success of the ISML-ITMT process is based upon making the Cr ineffective in retarding recrystallization of the worked ingot into a fine grain structure. The ISML-ITMT process accomplishes this by maintaining most of the Cr in supersaturated solid solution in the aluminum-rich matrix during both the partial homogenization and low temperature deformation stages. Subsequent recrystallization and homogenization of the ISML-ITMT material produces a fine grain structure followed by precipitation of the remaining Cr. DiRusso et al[7-9] state that a fine grain structure is not produced during conventional processing because in contrast to the ISML-ITMT process, the Cr precipitates during the initial thermal treatment prior to working. In addition, they state that dynamic recovery occurs during the working operation; this also hinders recrystallization into a fine grain structure.

Based on these results Frankford Arsenal carried out studies of experimental treatments examining not only the effect of Cr, but also the effect of Zn, Mg and Cu in producing fine grained wrought 7075 sheet. The processing steps involved in the experimental treatments used in this study as well as those used in ISML-ITMT and in conventional processing are shown schematically in Fig. 1 along with the corresponding grain morphologies. The details of the processing steps are given elsewhere.[10] The experimental ingot processing treatments involved those in which the Cr was precipitated out of solution prior to the initial deformation. As can be seen these treatments utilized a high temperature homogenization prior to the initial deformation step which has been shown by extensive electron microscopy studies to precipitate the Cr out of supersaturated solid solution in the

Al-rich matrix as the incoherent precipitate, $Al_{18}Cr_2Mg_3$ [11]. An example of this precipitation is shown in Fig. 2. The corresponding structure after the low temperature homogenization treatment in the ISML-ITMT process is shown in Fig. 3. The tensile properties of the materials in the T6 temper are presented in Table I.

It can be seen from Fig. 1 that the experimental techniques produced AR+HR sheet material having grain sizes that are finer than those produced using conventional processing. Also, it can be seen from Table I that the experimentally processed material has equivalent strength and significantly greater reduction in area than the conventionally processed sheet. With regard to the experimental treatments themselves, the grain size of the material processed according to Treatment 1 is much finer than that of material processed according to Treatment 2. This is especially true in the AR condition. The reason for the difference in the grain sizes will be discussed later. Also, the ISML-ITMT sheet has a finer grain size, equivalent strength and higher elongation and reduction in area than the conventionally processed sheet.

On comparing the experimental treatments with the ISML-ITMT technique, two points are evident. The first is that experimental Treatment No. 1 produced sheet which was equivalent to ISML-ITMT processed material. Specifically, it can be seen that the grain sizes of the materials produced by the two processes are essentially the same. Also, the tensile properties of the experimentally processed material and the ISML-ITMT material show the same significant improvement in ductility (Table I). The second point in this comparison is that the fine grain size achieved using Treatment No. 1 shows

that it is also possible to produce a fine grain recrystallized structure in 7075 without maintaining the Cr in supersaturated solid solution in the Al-rich matrix prior to the recrystallization homogenization step. Thus, it appears that Treatment No. 1 is important in that it forms the basis of another ITMT method (hereafter referred to as the Frankford Arsenal ITMT process or FA-ITMT), one in which the Cr is precipitated out of solution by a high temperature homogenization prior to the initial deformation step.

Since FA-ITMT processing produced a fine grain structure comparable to that produced using ISML-ITMT, it appears that there are other structural factors besides the Cr distribution that are important in determining whether or not a fine grain recrystallized structure can be produced in 7075. The obvious structural parameter is the distribution of the major alloying elements, Zn, Mg and Cu prior to the initial deformation and recrystallization step. The results of electron probe work to investigate this distribution are shown in Figs. 4 to 6. Regarding the FA-ITMT and ISML-ITMT techniques, both of which produce a fine grain recrystallized structure, it can be seen that the Zn, Mg and Cu are present as coarse precipitates prior to the initial deformation step. In contrast, in Treatment No. 2, which produced a grain structure that was much larger than that produced using either the FA-ITMT or ISML-ITMT processes, the Zn, Mg and Cu are in solid solution in the Al-rich matrix prior to the initial deformation step. (It should be pointed out that in this work, no attempt was made to resolve the distribution of the Zn, Mg and Cu on a finer scale than is possible using optical microscopy.) Thus, the work shows that the distribution of the major alloying elements, Zn, Mg and Cu has a significant effect

on the recrystallized grain size of 7075. Also, the work shows that by control of the distribution of the Zn, Mg and Cu, fine grained 7075 can be produced independent of the distribution of the Cr.

CHARACTERIZATION OF ITMT PROCESSED 7075 PLATE

The ISML-ITMT and FA-ITMT processes were also applied to thick products of 7075, i. e. 1 in. thick plate. The processing details are given elsewhere.[10] The grain morphologies of the ITMT plate material along with that of commercial 7075-T651 1 in. thick plate are given in Fig. 7.

It can be seen that the grain size of the AR FA-ITMT material is finer than that of the commercial 7075-T651. There appears to be a duplex structure in the AR ISML-ITMT 1 in. thick plate. However, the overall grain structure is also finer than that of the commercial 7075-T651. Although the duplex structure is not present in the FA-ITMT material, the grain size is somewhat larger than that in the fine grained areas of the duplex structure of the ISML-ITMT material. The reason for this may be related to the differences in the two ITMT processes or to differences in the temperatures of working. It was found that in the ISML-ITMT process, increasing the recrystallization temperature to 960°F eliminated the duplex structure and produced fine equiaxed grains[10].

With regard to the AR+HR condition, there is no indication of duplex structures in either the FA-ITMT or ISML-ITMT plates. Also there appear to be no significant differences between the grain structures of the materials produced using either ITMT process although both have a finer grain size than conventionally processed material.

The longitudinal and long transverse tensile properties and fracture toughness values of the ISML-ITMT and the FA-ITMT AR and AR+HR 1 in. thick plates in the T6, T76, T73 and FTMT tempers are shown in Table II. Several points are evident. ITMT processed 7075 plate 1 in. thick has equivalent strength and significantly better elongation and reduction in area than its conventionally processed commercial counterpart in the T6, T76 and T73 tempers. The tensile properties of ITMT processed 7075 plate 1 in. thick in the AR condition are equivalent to those in the AR+HR condition. The tensile properties of FA-ITMT and ISML-ITMT processed 7075 plate 1 in. thick are equivalent in the T6, T76 and T73 tempers.

The fracture toughness of the ITMT materials (determined using compact tension specimens (CKS) according to ASTM Method E399) in the AR condition is only slightly better than that of the commercial material whereas in the AR+HR condition the fracture toughness is significantly greater (Table II). Fractographic examination using the scanning electron microscope has shown that regardless of temper for both the ISML-ITMT and FA-ITMT processes, the fracture mode of the AR material is primarily intergranular (Fig. 8 is an example) while that of the AR+HR material is primarily transgranular. (Fig. 9 is an example). These differences in fracture mode can be correlated with the differences in fracture toughness values between the AR and AR+HR materials.

The data in Table II also show the benefits to be gained by combining FTMT with ITMT, i. e., ITMT+FTMT 7075 plate has both significantly higher strength and higher elongation and reduction in area than conventionally processed commercial 7075-T651 plate.

As in the case of the ITMT materials in the T6, T76 and T73 tempers, the fracture toughness values of the AR+HR materials in the FTMT temper are significantly better than those of the AR materials. This is especially pronounced in the longitudinal direction. The important point is that the ITMT+FTMT material, especially in the AR+HR condition, has significantly higher strength, ductility and toughness than the commercial 7075-T651 plate.

The stress corrosion testing results (obtained using C rings in alternate immersion in a 3.5% NaCl solution according to Federal Test Method Standard No. 151) are shown in Table III for the AR ITMT material and in Table IV for the AR+HR ITMT material. In general, it appears that the stress corrosion resistance of the ISML-ITMT material in both the AR and AR+HR conditions and of the FA-ITMT material in the AR+HR condition is better than that of conventionally processed 7075. The reasons for this are: (a) in the T6 temper the stress corrosion resistance threshold may be higher than the 7ksi threshold value for commercial 7075-T651,[12] (b) in the T76 temper the ITMT material appears to be better than the requirement of no failures after 30 days in alternate immersion at a stress level of 25 ksi[12] and (c) in the T73 temper the ITMT material appears to be equivalent to the requirement of no failures after 30 days in alternate immersion at a stress level equal to 75% of the yield stress.[13,14]

The stress corrosion resistance of the AR FA-ITMT material in the T6 temper appears to be higher than the threshold stress level for commercial 7075-T6, but in the T76 and T73 tempers, the AR FA-ITMT material does not satisfy the commercial specifications. This is probably because the FA-ITMT material in the AR condition may not offer as difficult a path to stress corrosion failure as does the FA-ITMT material in the AR+HR condition and the

ISML-ITMT material in the AR and AR+HR conditions. The stress corrosion resistance of the ITMT materials in the FTMT temper is essentially equivalent to that of commercial 7075 in the T6 temper. This is expected since the ITMT+FTMT materials had substantially higher strengths than does the commercial T6 material.

SUMMARY

Two new ingot thermomechanical processing techniques, ISML-ITMT and FA-ITMT, have been developed which upgrade the engineering properties of aluminum alloy, 7075. For a given standard temper, i. e., T6, T76 and T73, high purity ITMT processed 7075 alloy has finer grain size, equivalent strength and better ductility, fracture toughness and stress corrosion characteristics than its commercial counterpart. High purity ITMT processed 7075 alloy in the FTMT temper has higher strength, ductility and fracture toughness than commercial 7075-T6 material.

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Table I - Long Transverse Tensile Properties of Conventional and ITMT Processed 7075-T6 Sheet (0.160" Thick).

Process	Condition	Y.S. (.2% offset) ksi	U.T.S. ksi	E in 0.45" %	R.A. %
Exp. No. 1 (FA ITMT)	AR+HR	71.8	84.1	14.9	42.6
Exp. No. 2	HR	70.7	82.9	14.6	38.3
Conventional	HR	69.8	83.3	12.8	31.1
ISML-ITMT	AR+HR	71.0	84.0	14.6	44.5

Table II - Mechanical Properties of Conventional and ITMT Processed 7075 Plate (1 in. Thick)

		Longitudinal					Long Transverse				
Process	Condition	Y.S.(.2% offset) ksi	U.T.S. ksi	E in 2" %	R.A. %	K_{Ic} ksi$\sqrt{in.}$	Y.S.(.2% offset ksi	U.T.S. ksi	E in 2" %	R.A. %	K_{Ic} ksi$\sqrt{in.}$
T6 Temper											
Conventional	HR	76.4	85.2	10.0	14-17	25.5	72.8	82.5	9.5	14-16	20.5
FA-ITMT	AR	73.7	83.3	18.0	29.8	28.1	73.9	83.0	19.0	35.1	25.4
FA-ITMT	AR+HR	73.4	82.7	15.7	31.0	41.0*	72.9	82.1	17.8	40.8	26.6
ISML-ITMT	AR	74.6	83.6	17.5	29.4	27.6	73.7	83.2	18.2	29.6	30.7
ISML-ITMT	AR+HR	76.4	85.7	16.0	32.0	42.5*	73.8	82.6	16.8	38.9	34.0
T76 Temper											
Conventional	HR	68.0	78.0	12.0		27.1					23.8
FA-ITMT	AR	68.9	78.1	16.3	44.0	34.2	69.5	78.6	15.5	39.5	33.3
FA-ITMT	AR+HR	69.5	79.0	17.5	48.4	52.0*	67.2	76.3	15.3	43.3	46.9*
ISML-ITMT	AR	71.9	80.2	16.5	43.8	33.2	72.1	80.1	14.8	37.3	30.2
ISML-ITMT	AR+HR	70.5	79.7	14.3	42.4	59.9*	68.6	77.2	14.0	38.9	46.9*
T73 Temper											
Conventional	HR	66.3	76.7	12.0	29.0	31.5	64.6	74.9	10.5	20.0	28.2
FA-ITMT	AR	67.9	76.7	16.5	48.5	46.6*	66.5	75.6	16.0	45.1	40.4*
FA-ITMT	AR+HR	64.3	74.0	17.0	49.6	59.4*	64.6	74.2	15.4	42.9	53.3*
ISML-ITMT	AR	67.4	76.4	16.5	50.0	46.9*	66.6	75.5	14.5	38.4	39.5*
ISML-ITMT	AR+HR	65.9	75.4	16.1	51.2	65.3*	65.3	74.5	15.1	41.6	59.4*
FTMT Temper											
FA-ITMT	AR	83.8	88.1	13.7	37.4	22.6	81.4	87.5	12.2	34.6	20.8
FA-ITMT	AR+HR	85.8	89.3	12.8	24.8	34.6	82.3	87.9	11.7	25.4	22.7
ISML-ITMT	AR	88.3	91.4	12.0	28.2	25.4	83.2	89.1	11.2	25.2	20.5
ISML-ITMT	AR+HR	87.9	91.5	10.5	22.8	34.6	83.7	88.6	11.7	28.0	22.7

*K_Q - Excess Plasticity

Table III. Stress Corrosion Performance of As-Recrystallized ITMT Processed 7075 Plate 1" Thick Tested by Alternate Immersion in a 3.5% NaCl Solution.

Temper	E.C. % IACS	Long Y.S.ksi	Stress Level, ksi	F/N	Visual Examination Days to Failure	Metallographic Examination F/N	Metallographic Examination Days to Failure
ISML-ITMT							
T6	34.0	74.6	37.0	4/5	2,3,4,11,1 OK 90	4/5	2,3,4,11, 1 OK 90
			18.5	2/5	11,25,3 OK 90	4/5	11,25,90,90, 1 OK 90
			9.0	0/5	1 OK 90, 4 OK 90	0/5	5 OK 90
T76	37.9	71.9	50.0	1/5	11, 20K90, 20K90	1/5	11, 40K90
			45.0	0/5	10K45, 30K90, 10K90	3/5	45, 90, 90, 20K90
			40.0	0/5	10K45, 20K90, 20K90	0/5	10K45, 40K90
			35.0	0/5	10K30, 20K90, 20K90	0/5	10K30, 40K90
			25.0	0/5	10K30, 20K90, 20K90	0/5	10K30, 40K90
T73	41.2	67.4	50.0	0/5	10K30, 20K90, 20K90	0/5	10K30, 40K90
FTMT	33.7	88.3	25.0	5/5	2, 2, 2, 3, 3	5/5	2, 2, 2, 3, 3
			15.0	5/5	2, 3, 3, 4, 4	5/5	2, 3, 3, 4, 4
FA-ITMT							
T6	33.7	73.7	37.0	5/5	4,4,4,7,7	5/5	4,4,4,7,7
			18.5	4/5	10,11,12,12, 10K90	4/5	10,11,12,12, 1 OK 90
			9.0	0/5	2 OK 90, 3 OK 90	0/5	5 OK 90
T76	38.6	68.9	50.0	5/5	7,7,8,16,90	5/5	7,7,8,16,90
			35.0	1/5	15, 2 OK 90, 2 OK 90	1/5	15, 4 OK 90
			25.0	1/5	14, 2 OK 90, 2 OK 90	1/5	14, 4 OK 90
T73	40.6	67.9	50.0	5/5	6,7,9,83,90	3/5	6, 1 OK 7, 1 OK 9, 83,90
			35.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	0/5	1 OK 30, 4 OK 90
FTMT	34.9	83.8	25.0	5/5	2, 2, 2, 2, 2	5/5	2, 2, 2, 2, 2
			15.0	5/5	2, 3, 4, 11, 37	5/5	2, 3, 4, 11, 37

Notes: F/N = Number of failures/number of tests.

Line above numbers in days to failure column indicates those samples that were metallographically examined.

Table IV. Stress Corrosion Performance of As-Recrystallized + Hot Rolled ITMT Processed 7075 Plate 1" Thick Tested by Alternate Immersion in a 3.5% NACl Solution.

Temper	E.C. % IACS	Long Y.S.ksi	Stress Level, ksi	Visual Examination F/N	Visual Examination Days to Failure	Metallographic Examination F/N	Metallographic Examination Days to Failure
ISML-ITMT							
T6	31.3	76.4	25.0	5/5	4,4,4,4,7	5/5	4,4,4,4,7
			15.0	3/5	7,8,90, 1 OK 90, 1 OK 90	4/5	7,8.90,90, 1 OK 90
T76	38.0	70.5	50.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	1/5	1 OK 30,90, 3 OK 90
			35.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	0/5	1 OK 30, 4 OK 90
			25.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	0/5	1 OK 30, 4 OK 90
T73	40.0	65.9	50.0	0/5	1 OK 35, 2 OK 90, 2 OK 90	0/5	1 OK 35, 4 OK 90
FTMT	32.6	87.9	25.0	5/5	2, 2, 2, 2, 2	5/5	2, 2, 2, 2, 2
			15.0	5/5	3, 3, 4, 7, 52	5/5	3, 3, 4, 7,52
FA-ITMT							
T6	32.1	73.4	25.0	4/5	15,18,21,37, 1 OK 90	5/5	15,18,21,37,90
			15.0	1/5	21,2 OK 90, 2 OK 90	1/5	21, 4 OK 90
T76	39.7	69.5	50.0	2/5	2,5, 2 OK 90, 1 OK 90	2/5	2, 1 OK 5, 90, 2 OK 90
			35.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	0/5	1 OK 30, 4 OK 90
			25.0	0/5	1 OK 30, 2 OK 90, 2 OK 90	0/5	1 OK 30, 4 OK 90
T73	40.5	64.3	50.0	0/5	1 OK 35, 2 OK 90, 2 OK 90	0/5	1 OK 35, 4 OK 90
FTMT	32.6	85.8	25.0	5/5	2, 2, 2, 2, 2	5/5	2, 2, 2, 2, 2
			15.0	5/5	2, 2, 2, 2, 2	5/5	2, 2, 2, 2, 2

Notes: F/N = Number of failures/number of tests.

Line above numbers in days to failure column indicates those samples that were metallographically examined.

FIGURE CAPTIONS

Fig. 1. Schematic diagram of the various thermomechanical processes used.

Fig. 2. Microstructure of 7075 given the high temperature homogenization prior to the initial deformation in FA-ITMT showing the precipitation of $Al_{18}Cr_2Mg_3$. Mag. 50,000X.

Fig. 3. Microstructure of 7075 given the low temperature homogenization prior to the initial deformation in ISML-ITMT showing a slight precipitation of $Al_{18}Cr_2Mg_3$. Mag. 50,000X.

Fig. 4. Microstructures of 7075 given the homogenization step prior to initial deformation in Experimental Treatment 1 (FA-ITMT). (a) Keller's etch, (b) Backscattered electron image, (c) X-ray picture of Cu distribution and (d) X-ray picture of Zn distribution. Mag. 500X.

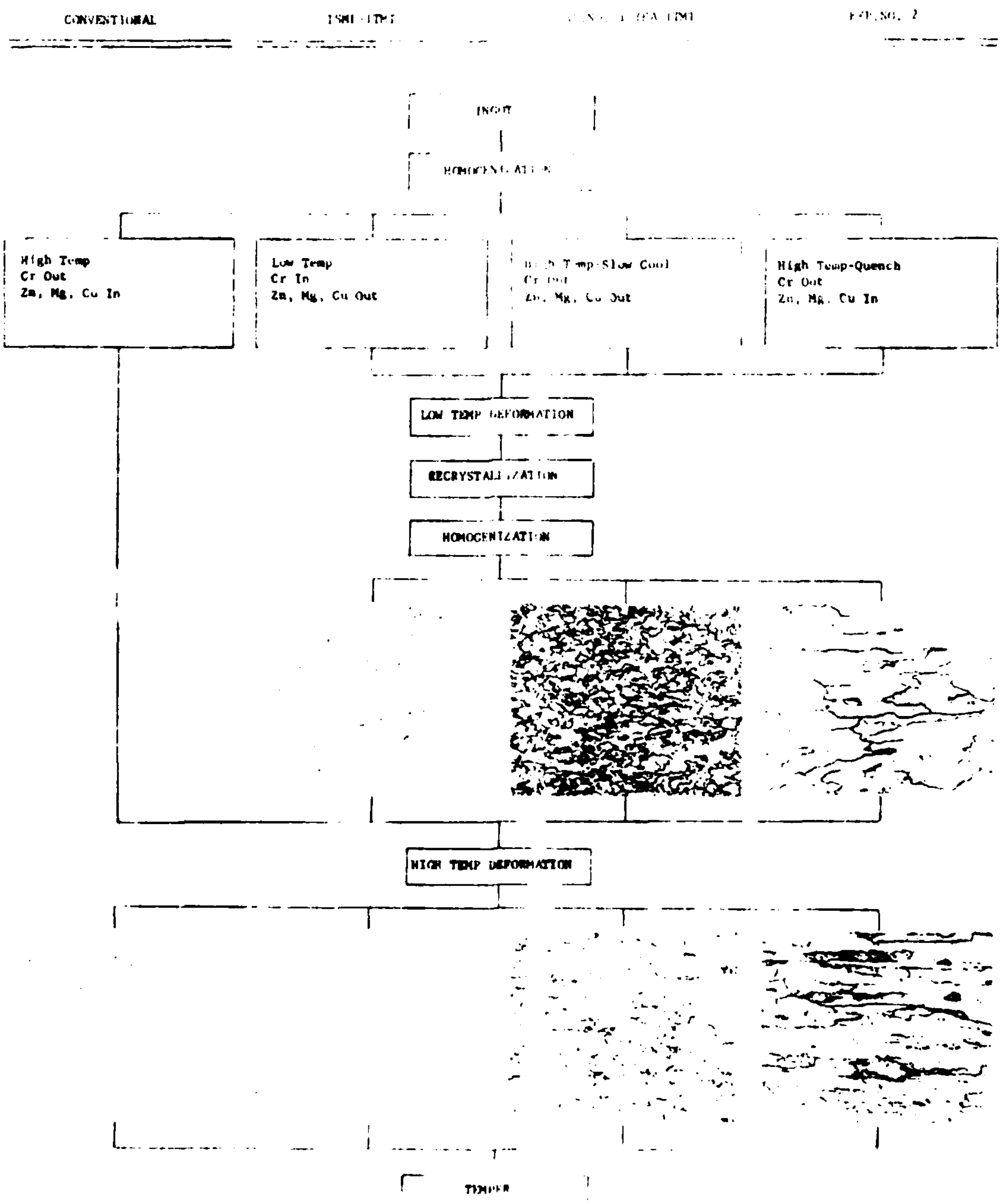
Fig. 5. Microstructures of 7075 given the homogenization step prior to initial deformation in Experimental Treatment 2. (a) Keller's etch, (b) Backscattered electron image, (c) X-ray picture of Cu distribution and (d) X-ray picture of Zn distribution. Mag. 500X.

Fig. 6. Microstructures of 7075 given the homogenization step prior to initial deformation in ISML-ITMT. (a) Keller's etch, (b) backscattered electron image, (c) x-ray picture of Cu distribution and (d) x-ray picture of Zn distribution. Mag. 500X.

Fig. 7. Conventional and ITMT Processed 7075-T6 Plate (1 in. thick). Longitudinal midplane sections. Mag. 100X. Keller's etch.

Fig. 8. Scanning electron micrograph of ISML-ITMT 7075-T73 in the AR condition showing primarily intergranular fracture. Mag. 300X.

Fig. 9. Scanning electron micrograph of ISML-ITMT 7075-T73 in the AR+HR condition showing primarily transgranular fracture. Mag. 300X.



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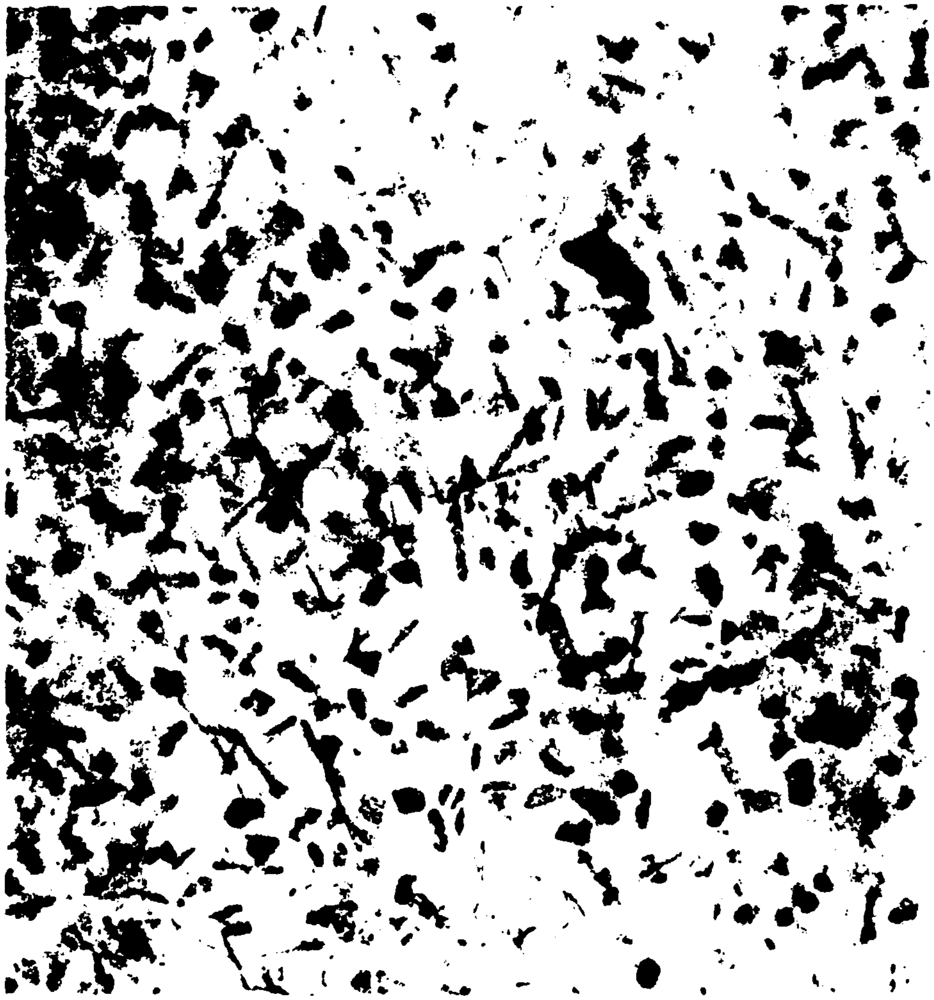

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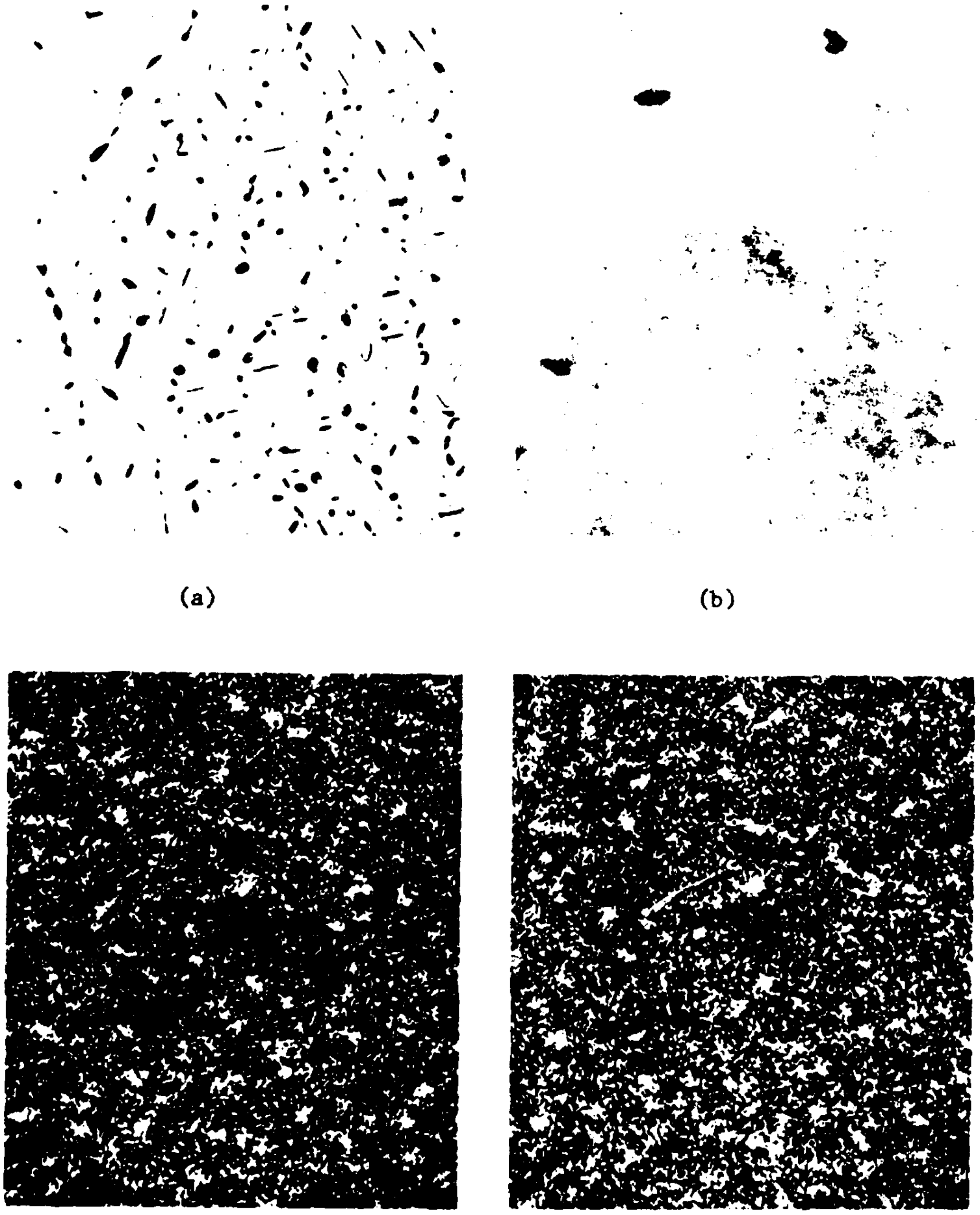

(a) (b)

(c) (d)

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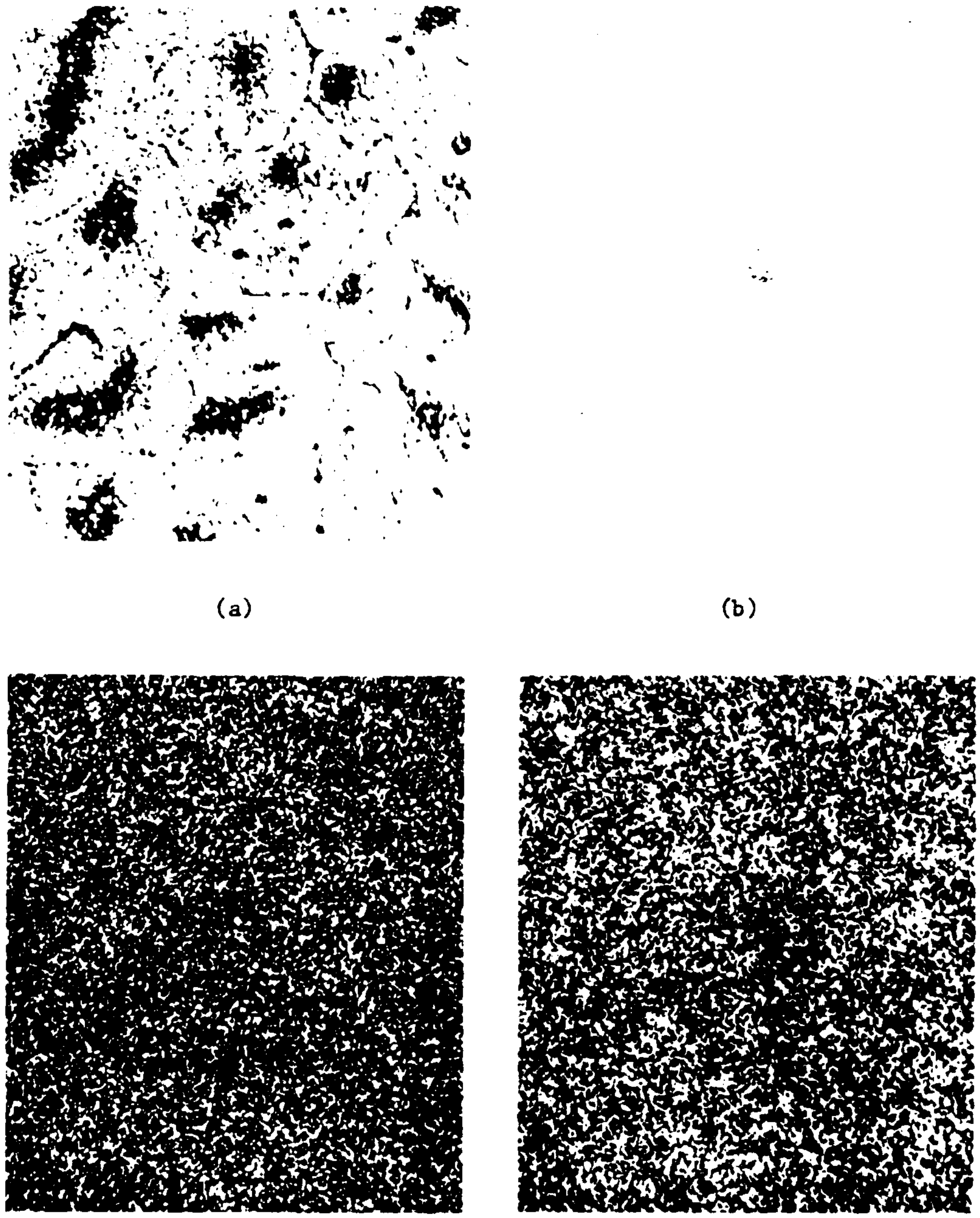
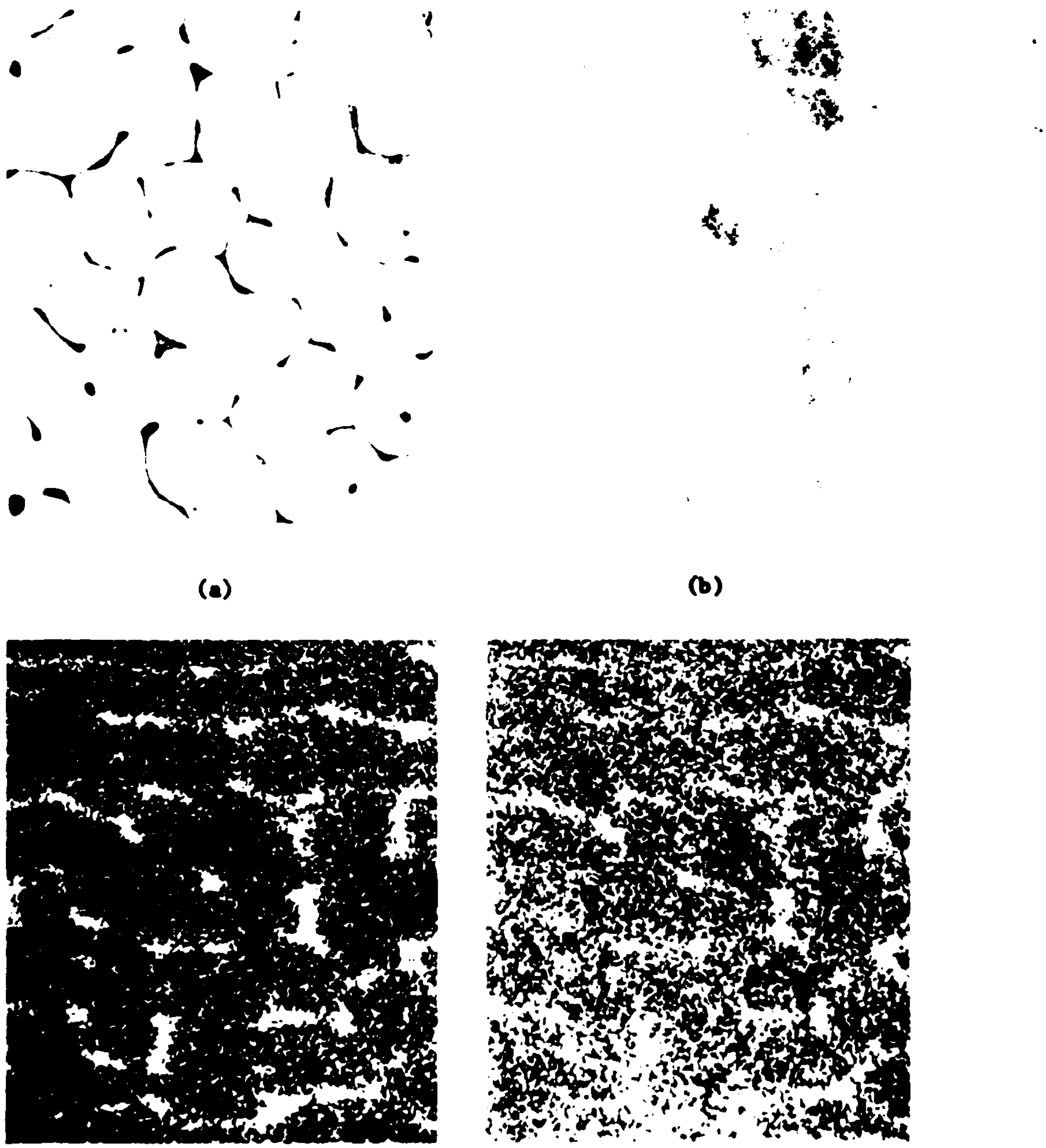


(a) (b)

(c) (d)

Fig. 5. Microstructures of 7075 given the homogenization step prior to initial deformation in Experimental Treatment 2. (a) Keller's etch, (b) Backscattered electron image, (c) X-ray picture of Cu distribution and (d) X-ray picture of Zn distribution. Mag. 500X.



(a) (b)

(c) (d)

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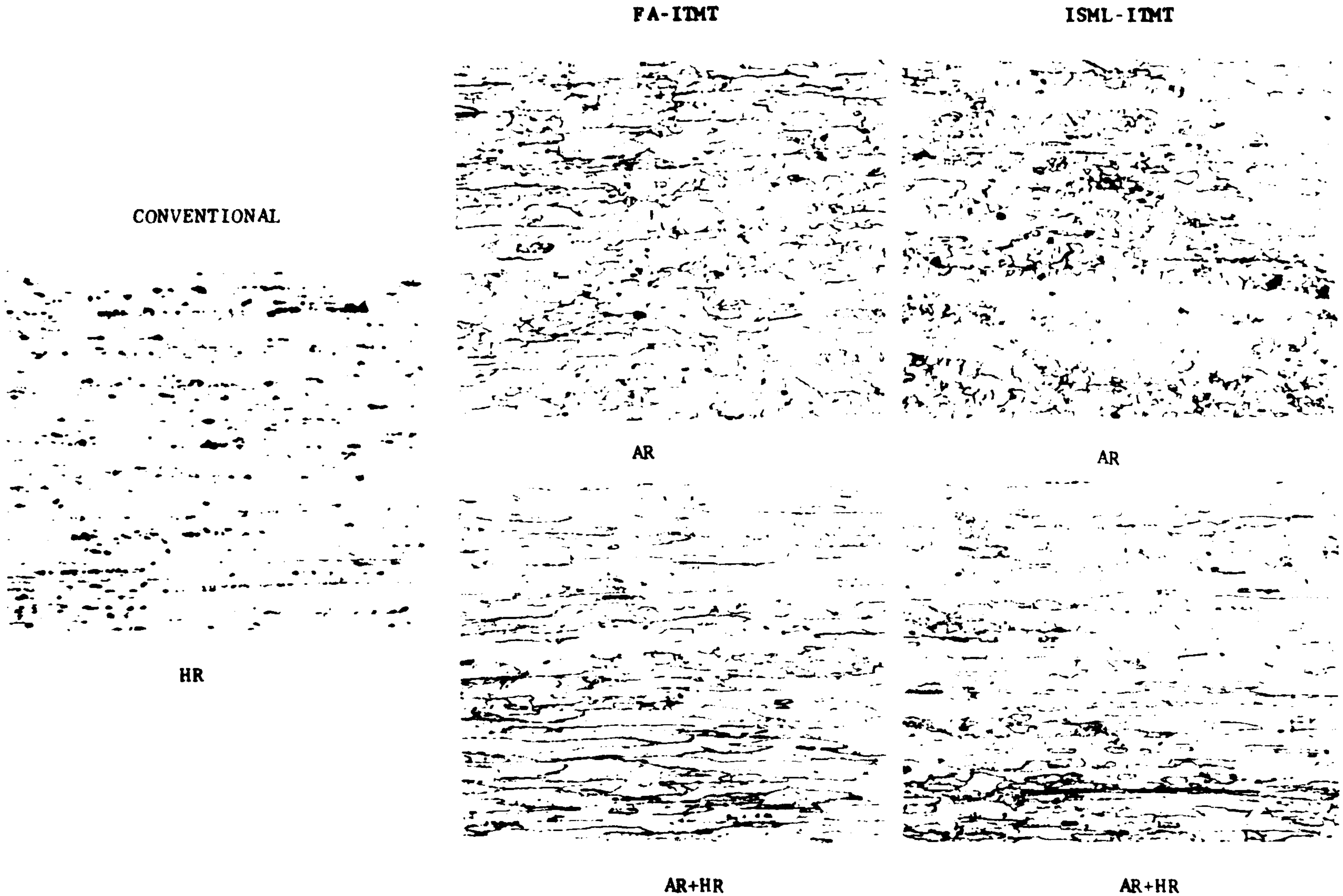

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